Climate Penalty of Ozone, Long Term Trends of $PM_{2.5}$ and PM_{10} Levels- Implications for Air Quality, Agriculture and Health Risk Assessment

Synopsis

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ORIGIN OF PROBLEM

According to the 6th assessment report of Inter-governmental Panel on Climate Change (IPCC 2021) it is unequivocal that human influence has warmed the global climate since the pre industrial times. There are multiple linkages that connect air quality with climate. Ozone (O_3) and particulate matter (PM) are two main contributors to non-attainment of air quality standards set up by World Health Organisation (WHO) and have negative impacts on vegetation and human health (WHO report 2021). Though several emission control strategies have been implemented there is a growing concern that elevated global temperatures may lead higher tropospheric ozone and PM concentrations in already polluted regions. Meteorological changes due to a warming climate may play a role especially for the days with the highest pollution levels. Thus, it is necessary to evaluate long term trends of elevated PM and ozone to understand anthropogenic impacts on global climate change and explore relationship with meteorology. Also, there is a need to quantify ozone metrics to assess impacts on human health, crop and climate. Climate penalty is one of the metrics for comparing climate impact. Several studies indicate that anthropogenic sources of air pollution have shifted from North America and Europe to Asia. The air quality in India is currently among the poorest in the world and Indo-Gangetic Plains (IGP) are worst affected. There are no studies available in India to analyse the impact of climate penalty on surface ozone. Studies on the high burden of death and disease due to air pollution and agricultural loss in cities of IGP are also limited. Since ozone and PM pollution is identified as one of the main threats on human health and ecosystems and there is need for continued vigilance and research into interaction between ozone, PM and climate connections.

1. INTRODUCTION AND LITERATURE SURVEY

Particulate Matter (PM)

The term particulate matter is used for variable mixture of particles suspended in air we inhale. They are ubiquitous in the atmosphere and play a central role in earth systems, climate and public health (Jacob et al. 2009, Lee et al 2012, Fuzzi et al. 2015). They serve as nuclei for cloud droplets and ice crystals involved in formation of cloud and precipitation. They can scatter or absorb radiation affecting the earth's energy balance. Their complex interactions with meteorology can lead to reduced visibility with haze formation. Windstorms, sea sprays, volcanic eruptions, wildfires, industrial

processes and burning of fossil fuels add these particles to the atmosphere (Kinney et al. 2018). PM consists of sulphate, nitrates, ammonia, sodium chloride, black carbon (BC), mineral dust and water (Fiore et al. 2015). They are separated on the basis of their size into $PM_{10,}$ $PM_{2.5,}$ PM_1 and $PM_{0.1.}$ The most health-damaging particles are those with a diameter of 10 microns or less (PM_{10}), especially fine particles of 2.5 microns ($PM_{2.5}$) and ultrafine particles smaller than 0.01 microns (Wang et al. 2017, Lu et al. 2021). PM is generated from human and natural sources, with PM_{10} and above often coming from dust generated in the environment. Combustion of fossil fuels, particularly coal, fuel oil, and diesel, are a significant source of $PM_{2.5}$.

There is a close relationship between exposure to high levels of PM and impacts on human health. Long-term exposure to $PM_{2.5}$ is associated with increased mortality due to lung diseases and cardiac events (Murray et al. 2020). The WHO has recognized PM as a carcinogen since 2013. In the last decade there has been increasing evidence that exposure to PM is a threat to human health even at very low exposure levels and WHO in its first update since 2005 has strengthened the air quality standards in September 2021. The 24-hour permissible limits for $PM_{2.5}$ and PM_{10} have been revised to 15 and 45µg/m^3 respectively and the annual limits for $PM_{2.5}$ and PM_{10} have been lowered to 5 and 15µg/m^3 respectively. It has also urged all countries to use these standards to help save millions of lives and address climate change crisis. India's National Ambient Air Quality Standards (NAAQS) were last revised in 2009, the 24-hour permissible limits for $PM_{2.5}$ and PM_{10} are 60 and 100µg/m^3 respectively and the annual limits for $PM_{2.5}$ and PM_{10} are 40 and 60µg/m^3 respectively.

Figure1 shows anthropogenic and natural sources of PM and ozone which are two major air pollutants. The emitted species which include CH_4, CO, non-methane volatile organic compounds (NMVOC), NOx, SO_2, NH_3, Organic Carbon (OC), Black Carbon (BC), dimethyl sulphide (DMS; from oceanic biota), mineral dust, and sea salt. Ozone is a secondary pollutant formed from oxidation of CH_4, CO, non-methane volatile organic compounds (NMVOC) in presence of NO_X and sunlight and some of it also comes from stratosphere. Air pollutants are impacted by climate change through physical changes affecting meteorological conditions and natural emissions.

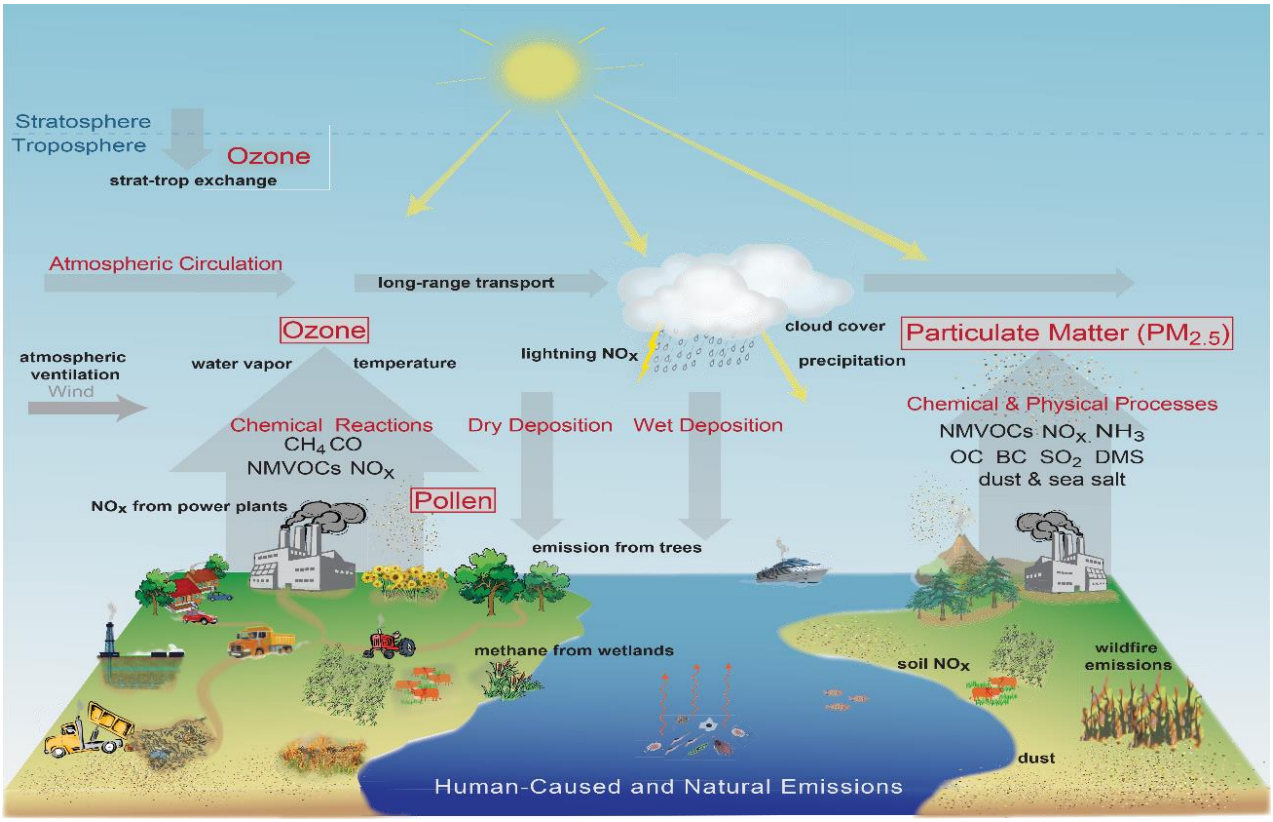

Figure 1 *Air quality and climate (Fiore et al. 2015)*

Ozone (O_3)

Ozone layer in stratosphere absorbs ultra violet (UV) radiation from the sun and protects life on earth. However, ground-level or tropospheric ozone is a secondary air pollutant which is detrimental to human health, crop and ecosystem productivity. It is an important greenhouse gas and a major component of smog. Increasing levels of ground-level ozone are due to man-made sources of air pollution. Ozone formation occurs when gases such as NOx, CO, CH_4 and volatile organic compounds are exposed to sunlight (Wang et al. 2017, Lu et al. 2021).

O_3 is photochemically produced in the troposphere when NO_2 molecules photolyze (at 420 nm wavelength) liberating O atom which combines with O_2 molecule to produce O_3.

$$NO_2 + h\nu \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

The O_3 so produced reacts with NO to produce NO_2. Thus, this reaction cycle constitutes a null cycle with no net O_3 production.

Net production of O_3 is initiated when VOC and CO are oxidized by OH radical, producing peroxy/ alkoxy radicals which react with NO to form NO_2. The NO_2 so produced photolyze to produce O which combines with O_2 to form O_3 (Sathe et al. 2021)

$$RH + OH^{\cdot} + O_2 \rightarrow H_2O + RO_2^{\cdot}$$

$$CO + OH^{\cdot} + O_2 \rightarrow CO_2 + HO_2^{\cdot}$$

$$HO_2^{\cdot} + NO \rightarrow NO_2 + OH^{\cdot}$$

$$NO_2 + h\nu \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

WHO and Indian NAQQS permissible limit of ozone is 100μg/m^3 for 8-hour daily maximum concentration. Short term exposure to ozone can cause breathing problems, trigger asthma, reduce lung function and cause lung diseases (Nawahda et al. 2020). There is now increasing evidence for long term exposure to ozone and episodes of mortality.

2.1 Climate Penalty of Ozone

Surface ozone is well known to have positive correlation with surface temperature (Bloomer et al. 2009, Tripathi et al. 2010, Coates et al. 2016, Fu et al. 2019). Warmer temperatures favour greater photochemical production rates of ozone. Pollutant accumulation is also favoured by meteorological conditions that are often associated with warmer weather like clear sky and relatively calm air flow (Lee et al. 2012). Also increased temperature leads to more natural emissions from biogenic and wildfire sources. It has been highlighted in several studies that rate of peroxyacetyl nitrate decomposition is enhanced at elevated temperatures which leads to local NO_2 and O_3 increase in polluted regions (Doherty et al. 2017).

Therefore, as global climate becomes warmer it is expected that surface ozone levels will rise in already polluted regions and emission control benefits will be reduced due to increase in surface temperatures. This potential effect of climate change on ozone is referred to as “ozone climate penalty” (Wu et al. 2008).

Varying definitions of the O_3−climate penalty have been presented in the literature. Wu et al. consider the climate penalty to represent either the additional decreases in NO_x emissions to counter any climate driven increase in O_3 (assuming NO_x is the due to the increase in O_3 due to a warmer climate). Bloomer et al. 2009 calculate the "ozone−climate penalty factor" as the slope of the best fit line between long-term observational measurements of O_3 and temperature. Other studies utilizing air quality models quantified the change in O_3 due to a prescribed temperature perturbation but did not refer to this sensitivity as a "climate penalty".

To assess the magnitude of the climate penalty bearing upon surface ozone two approaches can be adopted. A first approach consists in investigating correlations between daily ozone and temperature (either observed or modelled by means of short-term sensitivity simulations). In the second approach chemistry-transport models (CTMs) and chemistry-climate models (CCMs) under changing climate conditions are used (Rasmussen et al. 2013).

Prior to 2002 ozone increased ~ 3.2 ppbv/ºC over rural eastern US. After 2002 NO_x emissions were reduced by 43% and ozone levels fell by ~10 % and climate penalty factor dropped to ~2.2 ppbv/ºC (Bloomer et al. 2009). Over North America it was estimated that surface ozone will generally increase by 1–10 ppb in response to climate warming, particularly over present-day high-ozone areas such as North-eastern USA (Schnell et al. 2017). Over East Asia, Lee et al. 2012 simulated the influence of climate warming on surface ozone. They found a large reduction in annual mean ozone concentrations, particularly over North-eastern Asia, due to projected increase in precipitation and cloud coverage.

Over Europe, a synthesis of 25 model projections ascertained that climate warming is expected to bear a penalty on surface ozone over most parts of continental Europe while marginally reducing ozone in Scandinavia in the future (Colette et al. 2015). Jing et al. 2017 determined the ozone climate penalty in midwestern US and concluded O_3 in the Midwestern U.S. has become more dependent on temperature since 2008 than in 1999 to 2007, dry tropical weather caused O_3 to increase significantly. Air stagnation has become more frequent in the Midwest since 2008 and increased air stagnation enhanced the positive correlation between O_3 and temperature. Otero et al. 2021 reported a decreasing sensitivity of O_3 to temperature over time, coinciding with decreasing trends in high NOx concentrations in Germany. Over India, Pommier et al. 2018 projected a significant increase in surface ozone of + 2 ppb

over Northern India and a decrease of − 1.4 ppb over Southern India. Crooks et al. 2021 estimated the warm season ozone climate penalty on Colorado Front Range to be around 0.5-1 ppb for 8-hour maximum ozone concentration which delayed the attainment of ozone standards by around 2 years.

Though a number of studies in Asia have examined variations of ozone and its precursors with meteorological conditions, the only reported studies for climate penalty of ozone are from China. In India studies assessing the climate penalty of ozone have yet not been reported.

2.2 Impact of Meteorological Changes on Ozone and PM concentrations

As the concentrations of surface ozone and PM increase together with a changing emissions and meteorological conditions, understanding the relationships between meteorological variability and pollutant levels is crucial in air quality research and management. A number of studies highlight formation and accumulation of PM and ozone to be closely related to meteorological conditions (Wang et al. 2017, Fleming et al. 2018, Otero et al. 2018, Lu et al. 2019, Chen et al. 2020, Hong et al. 2020). A changing meteorology as a result of warming climate is expected to significantly affect pollution levels (Schnell et al. 2018, Porter et al. 2021).

Ventilation rates, dry/wet deposition, chemical conversion loss rate, natural emissions are affected by varied meteorology (Zhang et al. 2019). Temperature and early morning solar radiation were found to be the main predictors of aerosols in summers in Switzerland (Ordonez et al. 2005). A study of aerosol pollution in United States reported influence of relative humidity and temperature (Camalier et al. 2007). Downward trend of mean wind speed in China was conducive to accumulation of pollutants and rising number of fog-haze phenomenon (Liu et al. 2009). Weak Asian Winter monsoon reduced vertical gradients in horizontal wind and was related to heavy aerosol pollution. Diffusion of pollutants was unfavorable in Eastern China due to weak wind zones and downdrafts (Xu et al. 2015).

Doherty et al. 2017 reported effect of climate change on PM and ozone pollution and summarized impacts of meteorological variables on Ozone and PM concentration. Changes in temperature, water vapour, precipitation, cloud cover, meteorological transport and mixing influence air quality. Ozone is strongly corelated with temperature and higher temperature will lead to increased ozone levels due to rise in ozone precursors and higher chemical reaction rates. Overall effect of increased temperature on

PM is difficult to predict and depends on specific composition of PM. Increased temperature enhances sulphate aerosol formation but decreases nitrate PM (Figure 2).

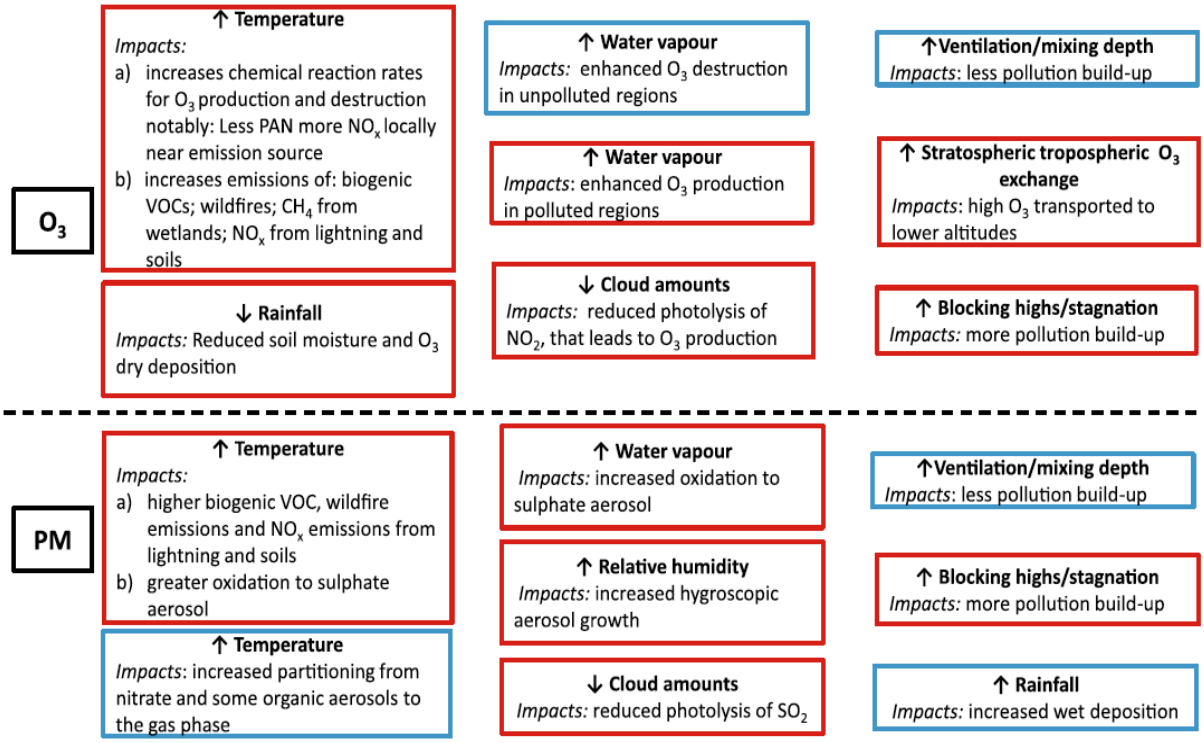
O3
↑ Temperature
Impacts:
a) increases chemical reaction rates for O3 production and destruction notably: Less PAN more NOx locally near emission source
b) increases emissions of: biogenic VOCs; wildfires; CH4 from wetlands; NOx from lightning and soils
↓ Rainfall
Impacts: Reduced soil moisture and O3 dry deposition
↑ Water vapour
Impacts: enhanced O3 destruction in unpolluted regions
↑ Water vapour
Impacts: enhanced O3 production in polluted regions
↓ Cloud amounts
Impacts: reduced photolysis of NO2, that leads to O3 production
↑Ventilation/mixing depth
Impacts: less pollution build-up
↑ Stratospheric tropospheric O3 exchange
Impacts: high O3 transported to lower altitudes
↑ Blocking highs/stagnation
Impacts: more pollution build-up
PM
↑ Temperature
Impacts:
a) higher biogenic VOC, wildfire emissions and NOx emissions from lightning and soils
b) greater oxidation to sulphate aerosol
↑ Temperature
Impacts: increased partitioning from nitrate and some organic aerosols to the gas phase
↑ Water vapour
Impacts: increased oxidation to sulphate aerosol
↑ Relative humidity
Impacts: increased hygroscopic aerosol growth
↓ Cloud amounts
Impacts: reduced photolysis of SO2
↑Ventilation/mixing depth
Impacts: less pollution build-up
↑ Blocking highs/stagnation
Impacts: more pollution build-up
↑ Rainfall
Impacts: increased wet deposition

Figure 2 *The impacts of meteorological and climate variables on O_3 and PM concentrations. ↑ represents an increase in the variable and ↓ a decrease. A Red (blue) box outlines depict where changes in a given variable predict an increase (decrease) in O_3 or PM. (Doherthy et al. 2017)*

A number of studies have been carried out in India to assess the impact of meteorological influence on PM and ozone concentrations (Yadav et al. 2019). A positive correlation of PM pollution with wind speed, negative correlation with temperature and a negative correlation with rainfall at Bhubaneshwar was reported by Mahapatra et al. (2017). For ozone pollution a study at Coimbatore, India observed positive correlation for temperature and windspeed but negative correlation for humidity (Manju et al. 2018). Due to meteorology about 68.5 % variability in PM_{10} was reported by Mukherjee et al. 2018 in Varanasi. The study suggested PM_{10} association with dew point, followed by wind speed, temperature and ventilation coefficient.

Krishna et al. 2018 state a positive correlation between wind speed and planetary boundary layer height with PM pollution over Delhi and Pune. Ozone showed a significant correlation with temperature and UV intensity in a similar study over IGP (Ravindra et al. 2019). During monsoon period a reduction of about 53% was reported in PM_{10} levels due to wet scavenging of aerosols in

Udaipur (Yadav et al. 2019). Dhaka et al. 2020 investigated close association of haze and development of $PM_{2.5}$ and observed that even in clear sky conditions haze formation could develop substantial amount of $PM_{2.5}$ in Delhi. They observed a rapid decline in $PM_{2.5}$ with increase in solar radiation.

2.3 Impact on Agriculture

Tropospheric ozone (O_3) being phytotoxic has an adverse impact on natural vegetation and crops (Cailleret et al. 2018, Fischer et al.2019, Unger et al. 2020, Feng et al. 2020). Its rising concentration in India particularly in Indo-Gangetic plains is a crucial issue posing threat to agriculture. Surface ozone hinders photosynthesis and the ability of land ecosystems to assimilate carbon from the atmosphere is reduced, consequently global warming is further increased. O_3-induced plant damage is mainly caused by the stomatal uptake of O_3 into the leaf interior (Heagle et al. 1989). In the intercellular spaces ozone quickly generates reactive oxygen species and causes oxidative stress (Booker et al. 2009). This leads to altered metabolic pathways, reduction in photosynthetic proteins, impaired reproductive development and accelerated senescence under oxidative stress. Accumulation of biomass in plants is lowered due to decreased carbon assimilation and alterations in its partitioning (McCrady et al. 2000). Reductions in crop yield and modifications in crop quality have been substantiated in a number of studies (Singh et al. 2017, Mills et al. 2018, Ainsworth et al. 2020, Saxena et al. 2020).

To assess the impacts of O_3 pollution on crop yields, several metrics have been developed based on results from both field and open-top chamber experiments. A few are concentration-based metrics, including daylight-hour growing-season average O_3 concentration like M7 or M12 (Mean daytime 7 hour or 12-hour surface ozone concentrations) and accumulated daylight O_3 concentration over certain thresholds (AOT40 which is accumulated exposure over a threshold of 40 ppbv and SUM06 which is sum of all ozone concentrations above 60 ppb). In AOT40 and SUM06 the baseline ability of plants to detoxify low levels of O_3 is considered, in accordance with which crops suffer yield losses only if the hourly O_3 concentration exceeds 40 (AOT40) or 60 (SUM06) ppb.

These metrics have been used extensively to evaluate global yield losses due to present-day O_3 concentrations, which are estimated to be 2–16% for the four major staple crops (wheat, rice, maize, soybean) (Ainsworth et al. 2017). Surface O_3 will have a progressively damaging impact on

future crop yields. In 2030 yields of wheat, soybean, and maize could be reduced by up to 26% globally and losses up to 17% are possible even in a hopeful scenario of future O_3. Agricultural losses worldwide may be worth $17–35 billion annually by 2030 (Avnery et al. 2011). Averaged over 2010-2012 it was estimated that ozone decreases wheat yields in the northern hemisphere by a mean 9.9% and 6.2% in the southern hemisphere (Mills et al. 2018). O_3 linked yield loss, relative to clean air, was 8% for rice and 6% for wheat as an average across China in 2015 (Feng et al. 2019). The spatial pattern of yield losses for a given crop is generally consistent across metrics though significant differences are reported in magnitude. Tai et al. 2021 evaluated the present-day globally aggregated yield losses to be 3.6 % for maize, 2.6 % for rice, 6.7 % for soybean, and 7.2% for wheat using the concentration-based and flux-based metrics together.

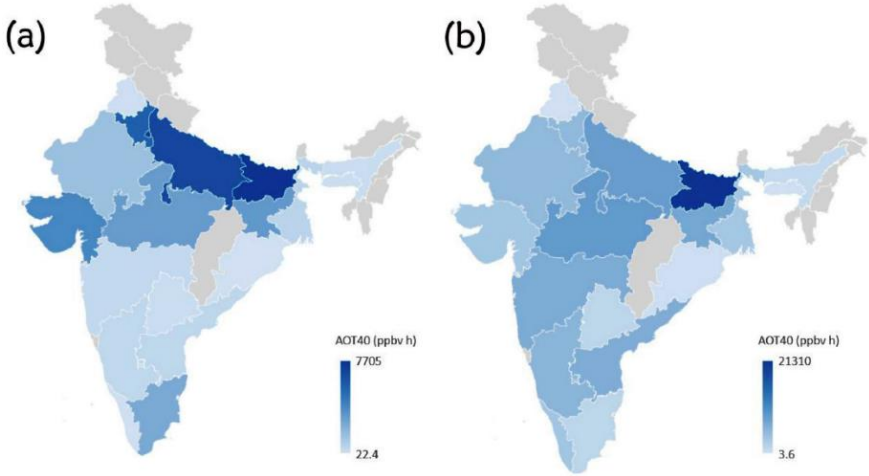

Figure 3. *AOT 40 values for (a) Kharif (June–October) and (b) Rabi (November–April) crop growing seasons of India. Daily daylight hourly O_3 levels above 40 ppb were calculated from individual monitoring station for each season. (Mukherjee et al. 2020)*

The IGP is one of the most fertile zones of Asia and is well suited for the cultivation of staple cereals and legumes and hence is called the bread basket of India (Burney et al. 2014). Highest burden of yield losses for a number of crops are reported in IGP one of the most fertile area in India (Figure 3). Major portion of the studies considering impact of O_3 on plant productivity in IGP have been carried out with rice and wheat which are two of the largest cultivated crops in India. Under ambient O_3 concentrations the order of sensitivity in major crops was wheat > mustard> rice>maize but the sensitivity of crops at elevated ozone levels varied with exposure dose, stomatal flux, intrinsic defence response etc (Mukherjee et al. 2020). Sinha et al. (2015) estimated the O_3 related yield losses based on

the AOT40 metrics for wheat, rice, cotton, and maize in Punjab. Relative yield losses (RYL) varied from 27 to 41% for wheat, 21–26% for rice, 9–11% for maize, and 47–58% for cotton. Sharma et al.2019 reported RYL for wheat to be 21-26 % and rice around 6% in India. The economic losses due to crop yield loss (CYL) was estimated close to 5 billion USD for wheat and 1.5 billion USD for rice. In northern India one of the most polluted regions annual loss of wheat was about 9 million ton and that of rice 2.6 million ton in eastern region. Total all India annual loss of 4.0 – 14.2 million ton for wheat and 0.3 to 6.7 million ton for rice are estimated (Lal et al. 2017). For 2010-2015 RYL at Agra for wheat induced by ozone exposure was found to be 6-15 % using and for Kharif rice was 7.2 to 7.5 % using AOT40 (Kumari et al. 2020).

2.4 Health Impact

Particulate air pollution is becoming a serious health concern in urban cities and annual premature mortality burden from ambient $PM_{2.5}$ and PM_{10} exposure is estimated to be large (Balakrishnan et al. 2019). It is associated with many health impacts, including chronic obstructive pulmonary disease (COPD) linked to enhanced ozone, and acute lower respiratory illness (ALRI), cerebrovascular disease (CEV), ischemic heart disease (IHD) and lung cancer (LC). Association of disability adjusted life years (DALYS) and economic loss with air pollution related health effects demand quantitative analysis for correctional measures in air quality (Landrigan et al. 2018)

Several studies have been done on health effects of PM and ozone pollution (Garcia Menendez et al. 2015, Lin et al. 2018, Rovira et al. 2020, Pandey et al. 2021). There was a 30% increase in the global premature mortality burden attributed to ambient air pollution exposure from 6.87 million in 2000 to 8.89 million in 2015. The mortality burden from ozone exposure increased globally by 17% from 1.11 million in 2000 to 1.3 million in 2015 (Chowdhury et al. 2020). Total DALYs associated with $PM_{2.5}$ and PM_{10} in China were 7.2 and 20.66 million in 2014-2015. During this period the economic cost of health impact due to PM_{10} was approximately US$ 304,122 million which was 2.94% of China's gross domestic product (Maji et al. 2018). Estimated premature mortality caused by exposure to both ozone and $PM_{2.5}$ in East Asia for the years 2000 and 2005 was around 316,000 and 520,000 cases respectively (Nawahda et al. 2012). High values of premature deaths due to $PM_{2.5}$ were reported in IGP (Figure 4). From 1999 to 2014 premature deaths attributed to $PM_{2.5}$ rose to 38% in the South-

Southeast Asia (SSEA). Stroke and IHD were the two principal $PM_{2.5}$ related diseases. India and Bangladesh were the major contributors of deaths in SSEA. An estimated 991,600 deaths in India were computed (i.e., 69% of total premature deaths in SSEA) (Shi et al. 2018). Southeast Asia is reported to have the second highest premature mortality globally where India is the main contributor (0.65 million per year) to $PM_{2.5}$ related deaths (Lelieveld et al. 2015).

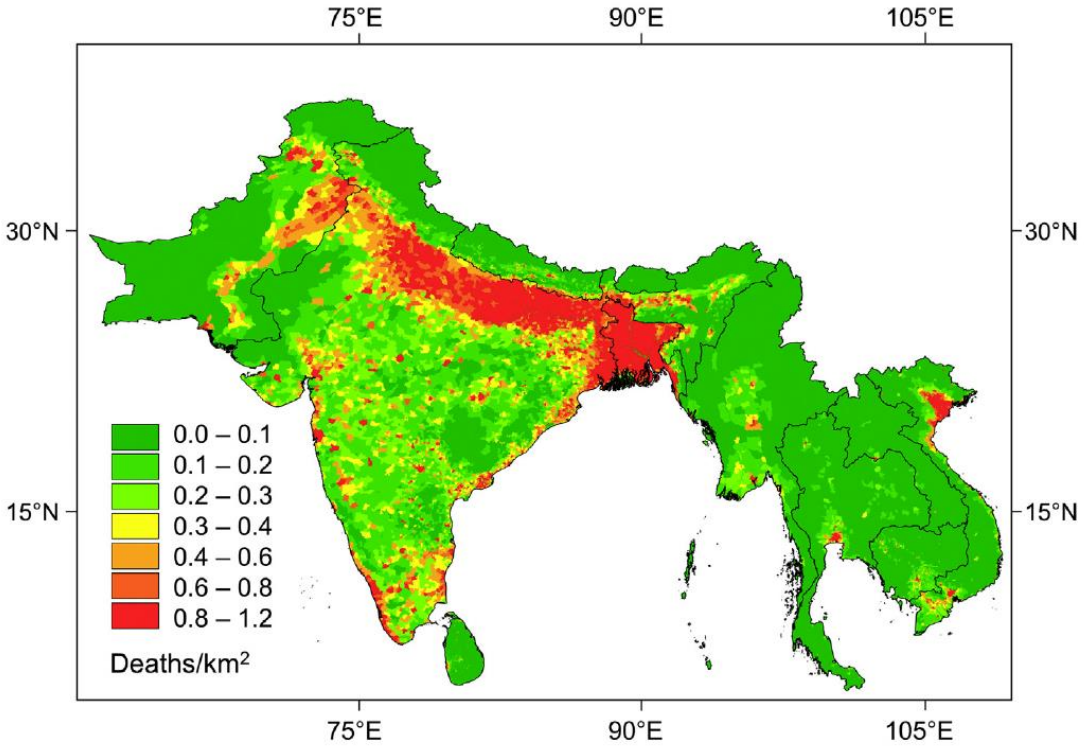

Figure 4. *Spatial distribution of the total average annual premature mortality (COPD, IHD, stroke, LC, and ALRI) in South and Southeast Asia from 1999 to 2014. (Shi et al. 2018)*

Health effects of particulate matter in India was also quantified in various studies. Premature mortality due to ambient $PM_{2.5}$ exposure was estimated to be 990,000 per year with 24,606,000 years of life lost (YLL). IGP accounted for 71% of the premature mortalities with Uttar Pradesh being the dominant state contributing 19% (Conibear et al. 2018). The Premature mortality due to CEV was 0.44 million, IHD 0.40 million and LC 0.01 million with a total of 1.04 million deaths in 2015. The states with highest premature mortality were Uttar Pradesh, Bihar and West Bengal. The highest total years of life lost (YLL) was 2 years in Delhi and Indo-Gangetic plains and eastern India had higher YLL than other regions (Guo et al. 2018). The estimated mortality burden attributable to $PM_{2.5}$ exposure in 29 cities of India was 114,700 deaths, with maximum mean deaths in Delhi (20,300). IHD is the major cause of

$PM_{2.5}$ related premature mortality accounting for 58% deaths, followed by stroke (22%), COPD (14%), LRI (4%), and LC (2%). The estimated child mortality rate attributable to $PM_{2.5}$ exposure is substantially high (10 – 15 deaths per 100,000 population) in the IGP region (Saini et al. 2020). For 2011 nationwide premature mortalities related to $PM_{2.5}$ exposure is about 570,000 people. Ozone related total premature mortality by COPD is about 31,000 people. In 2011 the economic cost of the premature mortalities in India associated with $PM_{2.5}$ and ozone are about 640 billion US$ (Ghude et al. 2016). In Varanasi 5700 premature deaths were reported annually which was 0.16% of the total population. Largest share of the burden was attributed to COPD (33%), followed by IHD (29 %), ALRI (19%), stroke (18 %) and LC (1%) (Jain et al. 2017). In Delhi, Mumbai, Kolkata and Chennai, the number of premature deaths related to $PM_{2.5}$ long term mortality were estimated in 2016 to be 14.8, 10.5, 4.8 and 4.8 thousand respectively (Maji et al. 2018). Global burden of disease study 2019 estimated about 1.67 million deaths in India due to air pollution and resulting economic losses were estimated 36.8 billion US$. Delhi had the highest per capita economic loss due to air pollution. Uttar Pradesh had the highest economic loss as a proportion of the state gross domestic product.

India with its 1.4 billion people is the fastest growing economy in the world and cannot afford to lose its health and economy to air pollution. Although there have been many publications on ozone and PM pollution but there are gaps in information about effects of air pollution on climate, agriculture and health in India. There is absence of information about climate penalty of ozone. Further health risk assessments studied that are available are mainly based on individual constituents like trace metals, BC, polyaromatic hydrocarbons (PAH) etc (Jena et al. 2017, Masih et al. 2017, Gadi et al. 2019, Kumar et al. 2020). Individual studies for long term assessment of health and agricultural losses are deficient. There is need to quantify different ozone metrics so that they can be used in health risk and crop damage assessment.

PROPOSED OBJECTIVES OF THE STUDY

According to World Meteorological Organisation (WMO) 2011-2020 is the warmest decade on record and global mean temperatures have risen 1.2^{o} C since preindustrial times. Rising temperatures affect ozone and PM. With a population of 1.4 billion the Indian economy faces several challenges and can do without the sabotaging effects of PM and ozone pollution which are silent killers. Thus, it is

necessary to examine long term variations in ozone and PM and quantify the health and economic loss especially in the Indo-Gangetic Plains which is one of the most populated and polluted regions in the world (Mukherjee et al. 2018). Therefore, the study has been planned with the following objectives.

1. Using long-term measurements of O_3 concentrations to assess changes in the climate penalty in summertime in specified cities of Indo-Gangetic plains.
2. To assess the effect of meteorological influence on seasonal and spatial variation of O_3 and $PM_{2.5}$ and PM_{10} in specified cities of Indo-Gangetic Plains.
3. Investigate the impact of elevated levels of ozone on agricultural crops.
4. Estimate the health risks due to ambient $PM_{2.5}$, PM_{10} and ozone pollution.
5. Case study on effects of air quality management in Dayalbagh, Agra.

1. METHODOLOGY

Objective 1- Climate Penalty of Ozone

Data Source

Pollutant data (Ozone, NO_X, CO) and meteorological parameter data (Temperature) will be extracted from Central Pollution Control Board (CPCB) air quality data base.

CPCB is a statutory organization and air quality monitoring is done under the National Air Quality Monitoring Programme (NAMP). Continuous Ambient Air Quality Monitors (CAAMQs) are used to collect data. Regular calibration of air quality monitors is reported to be done by CPCB in accordance with the instruction manual of the equipment for ensuring the quality of data (Hama et al. 2020).

The data will be screened for irregularities and removal of maintenance period. Data will be inspected for zero values and outliers.

Cities: - Delhi, Agra, Kanpur, Varanasi

Site Description

More than 48 million people live in Indo-Gangetic plains which is one of the most polluted regions in the world.

- Delhi is situated at the banks of river Yamuna and New Delhi is the world's most polluted capital (IQ Air Report Quality 2020). The chief sources of air pollution are exhaust from

vehicles, heavy industries like power generation, small-scale industries such as brick kilns, suspended road dust due to vehicle movement and construction activities.

- Agra, Kanpur and Lucknow are major industrial and most populous cities in Uttar Pradesh with worst air quality in the world. Agra is situated in western UP on the banks of river Yamuna and is at an altitude of 169 meters above sea level. The economy of Agra is mainly agriculture based and the main industries comprise of electrical goods, leather goods, steel rolling and metal products.
- Kanpur, the largest city in the state of UP, lies between river Ganga and Pandu. It is well known for its garment and leather industry and has a number of highly polluting tanneries, power plants and fertiliser units. Industrial sector is the biggest cause of air pollution in Kanpur (CPCB, National Summary Report, 2011).
- Lucknow the capital city of UP is located on the north western bank of Gomti River. Pollutants from various industries like chemicals, machine tools, aeronautics, furniture, textiles along with increasing energy consumption are adding to the problem of air pollution in the city.

The data availability for the same time period was ensured before finalizing these stations.

Time Period: - Decadal

Method

The most common metric to represent climate penalty will be adopted which is slope of the best fit line between long term daily maximum 8-hour ozone (MDA8) concentrations and daily maximum temperature.

Regression methods will be used as adopted by Jing et al. 2017 (Second order regression) / Otereo et al. 2021 (Ordinary least square regression).

<u>Objective 2- Meteorological Influence on PM and Ozone</u>

Data Source

Pollutant data ($PM_{2.5}$, PM_{10}, Ozone, NO, NO_2, NO_X, CO, SO_2, Benzene) and meteorological parameter data (Ambient Temperature, wind speed, wind direction, relative humidity, solar radiation) will be extracted from Central pollution control board (CPCB) air quality data base which uses instruments of high accuracy and precision (Dhaka et al. 2020).

Cities: - Delhi, Agra, Kanpur, Varanasi

Method

Impact of metrological influence will be examined on ozone and PM concentration in cities of Delhi, Agra, Kanpur, Varanasi on decadal scale. Statistical analysis like trend analysis, time series analysis, seasonal trend decomposition (STD) will be done.

Different Ozone metrics which have applications in human health and vegetation damage will be computed like 4th highest daily maximum 8-hour ozone (4MDA8), number of days with MDA8 > 70 ppb (NDGT70), SOMO35 (annual Sum of Ozone Means Over 35 ppb), AOT 40 (sum of difference between hourly ozone concentration and 40 ppb for each hour when the concentration exceeds 40 ppb in growing season).

In order to compute air parcel trajectories to determine the direction and distance of a parcel of air Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) will be used. The model calculation method is a hybrid between the Lagrangian approach and the Eulerian methodology. The dispersion of a pollutant is calculated by assuming either puff or particle dispersion.

<u>Objective 3- Agricultural Impact</u>

Data Source

Pollutant Data - O_3 will be extracted from Central Pollution Control Board (CPCB) air quality data base.

The data of crop production and minimum support price from crop (MSP) of wheat and rice for respective years will be taken from the database of the Commission for Agriculture Costs and Prices (Directorate of Economics and Statistics, Department of Agriculture and Cooperation.)

Cities: - Delhi, Agra, Kanpur, Varanasi.

Time Period: - 2011 onwards

- Method- AOT40 (Accumulated exposure over a threshold of 40 ppb)
- AOT40 is defined as the sum of differences between the hourly O_3 concentration and 40 ppb for $[O_3] > 40$ ppb during the crop growing season

  $$\boldsymbol{AOT40} = \sum_{i=1}^{n} ([O_3] - 40) \quad \text{for}[O3]>40\text{ppb}$$

  The relative yield loss, crop production loss and economic loss will be estimated for wheat and rice.

- The ozone-exposure dose response functions for relative yield (RY)

$\boldsymbol{RY} = -0.0000161 * AOT40 + 0.99$ Mills et al. (2007) Wheat

$\boldsymbol{RY} = -0.0000039 * AOT40 + 0.94$ Mills et al. (2007) Rice

$\boldsymbol{RYL_i} = 1 - RY_i$ RYL_i is relative yield loss for the respective year.

RY_i is relative yield in the respective year.

$\boldsymbol{CPL_i} = (RYL_i * CP_i)/(1 - RYL_i)$ CPL_i is crop production loss for the respective year.

CP_i is crop production in the respective year.

Economic cost loss (ECL_i) for a crop in a given financial year is defined as the financial loss due to O_3-induced damage. The minimum ECL is calculated on the basis of corresponding minimum support prices (MSPs) for the crop during the same fiscal year using the following equation (Kumari et al. 2020):

$\boldsymbol{ECL_i} = CPL_i * MSP_i$ ECL_i is economic cost loss for the respective year.

MSP_i is the minimum support price for crop in the respective year.

<u>Objective 4- Health Impact</u>

Data Source

Pollutant Data - ($PM_{2.5}$, PM_{10}, Ozone) will be extracted from Central Pollution Control Board (CPCB) air quality data base.

Population count and age structure data will be taken from Census Commissioner, Government of India.

Cities: - Delhi, Agra, Kanpur, Varanasi.

Method

Impact assessment $PM_{2.5}$, PM_{10}, O_3 will be done using AirQ+ (Version 2.1) for the highly polluted cities of Delhi, Agra, Kanpur, Varanasi.

Mortality assessment for $PM_{2.5}$ will be done.

All calculations performed by AirQ+ are based on methodologies and concentration–response functions established by epidemiological studies (Ansari et al. 2019). The concentration–response functions used in the software are based on the systematic review of all studies available until 2013 and their meta-analysis. AirQ+ will be used to assess particular health effects due to ozone and $PM_{2.5}$

pollution, impact on burden for lower pollution scenarios and magnitude of change in health effects in future compared to present scenario. Health effects considered in the present study will be long term mortality, chronic obstructive pulmonary disease, lung cancer, ischemic heart disease and stroke.

This model is based on the attributable proportion (AP). The attributable proportion is the fraction of the health outcome, which can be attributed to the exposure in a given population (assuming there is a causal association between the exposure and the health outcome and no major confounding effects on this association) for certain time period and can be calculated using the equation (Ansari et al. 2019)

$AP = \Sigma \{[RR(c) - 1] * p(c)\}/\Sigma [RR(c) * p(c)]$

where: RR(c) - relative risk for the health outcome in category c of exposure

p(c) - proportion of the population in category c of exposure

<u>Objective 5- Case Study on Air Quality Management</u>

Data Source

Pollutant data ($PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, CO) and meteorological data (temperature, humidity, rainfall, UV, wind direction, wind speed, solar radiation) at different stations will be measured using Polludrone (OIZOM).

Site – Dayalbagh, Agra

This is self-standing colony with open garden setting layout. Due to severe air pollution in Agra several proactive measures are being taken to improve air quality in this area. Regular air quality monitoring is done at different locations using Polludrones by Oziom which use a patented e-breathing sampling technology. Permission for entering and driving inside the colony is restricted to permitted vehicles. Residents and visitors are encouraged to use cycles or public electric vehicles for commutation. Importance is also given to use of solar energy with a number of residents using solar panels for electricity generation. Use of air conditioners is prohibited. No stubble burning is practiced in the surrounding farmland area. Misting with fine water droplets as also done to improve air quality. The site has been selected as deliberate, continuous and consistent efforts are being made for abatement of air pollution and thereby enhancing health and quality of life of the inhabitants.

Method

Comparison of PM $_{2.5,}$ PM_{10}, NO, NO_2, O_3 concentrations will be done with other stations in Agra. Crop loss assessment for Dayalbagh will be done for wheat and rice using AOT 40 method. Health impact assessment $PM_{2.5}$, PM_{10}, O_3 will be done using AirQ+ (Version 2.1).

2. EXPECTED OUTCOMES

1. The study will give insights into climate penalty of ozone in cities of Indo-Gangetic plains and impacts of NO_x reductions in the ozone temperature relationships.
2. The study will enhance understanding of influence of meteorology on ozone and PM pollution.
3. The study would provide quantitative estimates of crop reduction and yield loss for wheat and rice due to ozone pollution.
4. The study will provide magnitude of impact of $PM_{2.5}$, PM_{10} and ozone pollution on human health.
5. The study will create awareness about the gravity of air pollution problem and associated economic losses.

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